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Photometric lens-aperture measuring equipment

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PHOTOMETRIC LENS-APERTURE MEASURING EQUIPMENT

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PHOTOMETRIC LENS-APERTURE MEASURING EQUIPMENT

SUMMARY

A photometric lens-aperture measuring set is described by means of which lenses can be calibrated in terms of the 'T' number. The apparatus can deal with lenses whose focal lengths lie within the range 1 in. to 40 in. (2·54 cm to 1·02 m). The system used is similar to that used by M.G. Townsley[1] and consists of a comparison method in which two beams of light are used, one to provide light for the lens under test and the other as an accurately calibrated reference against which the comparison is made. The comparison is carried out by means of an integrating sphere fitted with a photocell. A chopper wheel is used to modulate, alternately, each beam of light, and an oscilloscope display is used for observation. This method and equipment has been selected not only for its accuracy but also for its versatility.

1. INTRODUCTION

It has been the normal practice to calibrate lens apertures in terms of 'f' number, (i.e. approximately the ratio of the focal length to the diameter of the entrance pupil*). It will be appreciated that 'f' number does not take into account losses incurred in the passage of light through the lens. Further, most lens irises are not circular, but of polygonal shape, making the measurement of area more difficult.

Some years ago, it was suggested that a photometric value or T number should be used in order to give a more accurate assessment of the light-gathering behaviour of a lens.

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* At small apertures, the above ratio is sufficiently accurate for all practical purposes. The more general formula is,

$$\text{f number} = \frac{1}{2\mu \sin\theta}$$

where μ = refractive index of image space,

and θ = angular semi-aperture of the exit pupil with the lens focused on infinity.

See Appendix for a more complete statement.

At the time the suggestion was made, the transmission of light through a lens rarely exceeded 65% (except for very simple lenses), and the use of f numbers demanded individual correction factors for lenses. It was quite common for exposure errors of two to one to arise when changing lenses, of apparently equal f-number, in a photographic camera.

When anti-reflection coating (or blooming) of lenses became common practice, transmission values of up to 90% were obtained and the suggested T-number system fell into abeyance.

There remained, however, the problem of the difference between the light transmissions of lenses having equal focal lengths but different construction (e.g. a fixed focal-length lens and a zoom lens). The fixed focal-length lens might have a transmission of 90%, whereas that of the zoom lens, due to the large number of elements used in its construction might only reach 70%. Thus, equality of geometrical aperture would not ensure equal image brightness on the photo-cathode of the camera tube in a television camera. In the case of a television studio, it must be realized that a difference of one stop between lenses doubles the amount of incident light required, with consequent problems of cost. T-number calibration obviates this difficulty by giving a correct photometric assessment of the lens behaviour, and this is in fact the practice in specifying lenses for television.* The depth of field is determined by the f-number rather than the T-number, but depth of field requires less accurate specification than does illumination.

2. METHOD OF MEASUREMENT

One simple photometric method of calibrating a lens in terms of T-number involves the use of a number of metal plates having circular apertures equal to the nominal apertures required by the specification of the lens. Each plate is placed in the path of a collimated beam of light and the flux traversing the aperture in the plate is measured. The lens under test is then substituted for the plate and the lens' iris adjusted until the flux emerging is equal to that obtained using the plate. This method is accurate but a set of plates has to be provided for each focal length of lens. This method is best suited to testing associated with mass production and the calibration of a very restricted range of lenses; considerable short-term stability of the light source is also demanded.

To obviate these difficulties, a two-beam system was chosen. The intensity of one beam, which is used for comparison, is calibrated directly in T numbers and focal lengths. A second collimated beam, derived from the same light source as the first, is used to illuminate the lens under test; this beam has substantially constant intensity over its cross-section and its diameter is sufficiently large to cover the range of lenses used in television.

The two beams are interrupted alternately, at a frequency of 1000 c/s by means of a chopper wheel rotating in front of the two originating apertures. The two light beams, after passing through a standard aperture and the lens under test respectively, are collected in an integrating sphere fitted with a photocell. The fact that the two beams are interrupted alternately by the chopper wheel results in a photocell output consisting of two trains of pulses. The iris of the lens under test is then adjusted until pulse trains of equal magnitude are produced in the photocell output. The use of a chopper wheel and two beams means that a.c. (and not d.c.) amplification of the photocell output is required and, further, a narrow band-pass filter can be used having a centre frequency equal to the fundamental frequency at which each of the two light beams is interrupted. When the two pulse trains obtained from the photocell are of equal magnitude the component at fundamental frequency is zero and a null balance is obtained on an oscilloscope. The band-pass filter also substantially reduces the noise level and enables the apparatus to be used in conditions of ambient light.

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* BBC Specification of lenses for Television TV 88/2.

To obtain other T numbers, the light flux in the comparison beam is adjusted by means of standard aperture plates whose aperture diameters vary in ratios of $\sqrt{2}$, corresponding to a difference of one stop between plates.

It should be added that the equipment measures or calibrates the lens for parallel light only (i.e. the source at infinity). It is the normal practice, however, to mark lenses with their f and T numbers in terms of a source at infinity and allowance is normally made for the reduced relative aperture when working at finite conjugates (see Appendix).

3. DESCRIPTION OF APPARATUS

As shown in Fig. 1, (and illustrated by a photograph of the apparatus in Fig. 2) the system consists of a light source 'S' illuminating two apertures 'a' and

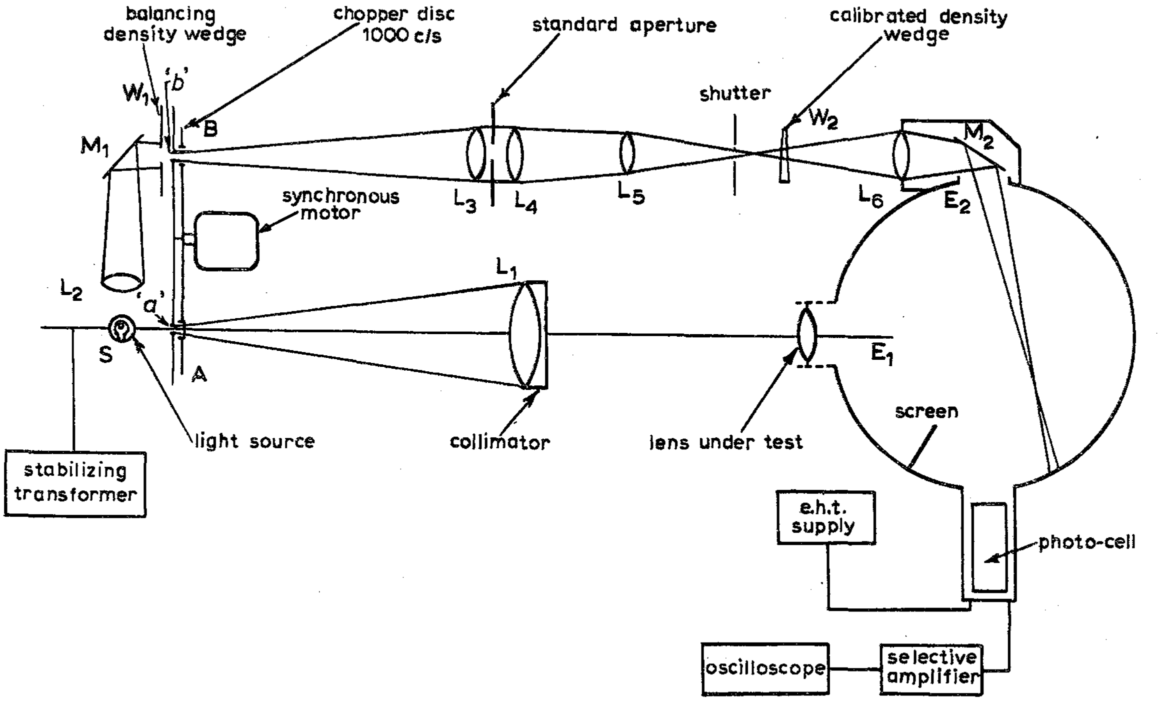

Fig. 1 - Schematic of the apparatus

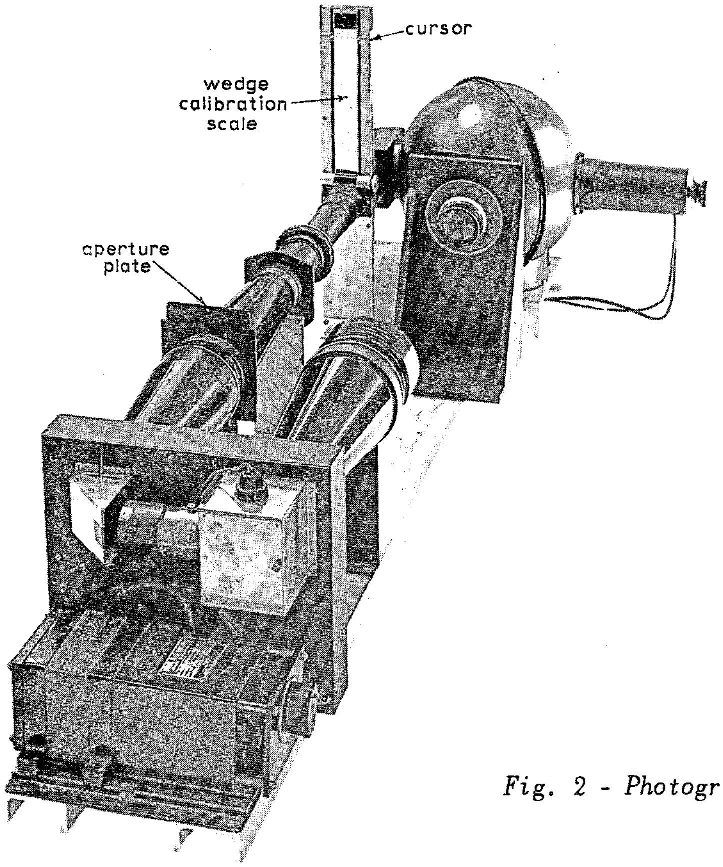

Fig. 2 - Photograph of apparatus

'b', 'a' being at the focus of a collimator and 'b' forming the effective source of the comparison beam. A chopper wheel with 40 equispaced apertures is rotated at 1500 r.p.m. by means of a synchronous motor and interrupts both beams, producing light pulses in each beam at the rate of 1000 c/s. When the light from one aperture is transmitted by the chopper the other aperture is masked; thus the two trains of light pulses are interlaced in time and a null in the photocell amplifier output is produced when the light beams are balanced because the amplifier has zero amplification at d.c.

Beam A is collimated by a high quality 20 in. (508 mm) lens L_1. As stated previously, a requirement of beam A is that it should have an even distribution of light intensity across its cross-section and this is obtained by using an opal lamp S as the source. The lens under test is situated in the path of beam A, in front of the integrating sphere aperture E_1. A slide holder is also provided to accommodate standard plates used for calibration, prior to measurements.

Beam B is the comparison beam. From Fig. 1 it can be seen that the light source illuminates the aperture 'b' via lens L_2 and mirror M_1. A neutral-density wedge W_1 is used to control the light flux in order to balance the two beams of light; this will be discussed later. The light from 'b' is then collimated by lens L_3 to provide a parallel beam in the space between L_3 and L_4, where standard aperture plates can be inserted to control the reference light flux. Lens L_4 collects the light transmitted by the standard aperture plate and in conjunction with lens L_5, neutral-density wedge W_2, lens L_6 and mirror M_2 conveys it to the integrating sphere. The main purpose of lens L_5 is to converge the beam so that only a small pencil of light is incident on the surface of the wedge, thus keeping the latter to a reasonable size; too small a beam would also be unsuitable as it would make the calibration of the wedge less reliable should dust collect on the surface of the wedge. Lens L_6 and mirror M_2 are used to direct the light into the sphere.

Thus the sphere has two beams of light entering it. Beam B gives rise to flux proportional to the area of transmission of the standard aperture plate and to the transmission of the wedge W_1, and beam A gives rise to a beam that is proportional to the light traversing the lens under test.

The photocell used is an RCA Type 6721 photomultiplier, supplied from a conventional EHT supply unit. The photocell selective amplifier and oscilloscope are also of conventional type.

3.1. The Standard Aperture Plates and Calibrated Wedge

Accurate circular holes cut in metal plates provide a series of standard apertures corresponding to one stop difference between plates.

The diameters of the holes vary from 0·0312 in. (0·0792 cm) to 2 in. (5·08 cm) in steps of ratio $\sqrt{2}$, (e.g. the 2 in. (5·08 cm) diameter aperture plate corresponds to T2 for an ideal lens of 4 in. (10·16 cm) focal length and 100% transmission; the next smaller plate with aperture diameter of 1·41 in. (3·581 cm) corresponds to T2·8 for the same focal length).

If, however, the lens under test has a 2 in. (5·08 cm) focal length, a 1 in. (2·54 cm) diameter aperture plate is required, in order to obtain the T2 calibration point. Alternatively, the light flux through the 2 in. (5·08 cm) standard aperture plate may be attenuated by a factor of 4, so as to be equivalent to that obtained from a 1 in. aperture, and this may be carried out by inserting a neutral-density filter of density 0·6 in the comparison beam. It can thus be seen that, when used in conjunction with neutral-density filters, a fixed number of aperture plates can cover a wide range of focal lengths and apertures. Furthermore, if the neutral-density filter is in the form of a calibrated wedge, a continuous range of focal length can be covered. It is convenient to make the calibration of the wedge directly in terms of equivalent focal length.

3.2. Calibration of Standard Plates and Neutral-density Wedge

Although the equipment may be used in other ways, it has been calibrated so that, for a lens of accurately known focal length in the range 1 in. to 64 in., (2·54 cm to 1·62 m) it is a simple matter to adjust the iris of the lens under test to correspond to the standard values of T-number (i.e. T2, T2·8, T4, T5·6 etc.).

The calibration procedure may be illustrated using the aperture plate shown in Fig. 3. This aperture has a diameter of 2 in. (5·08 cm) and serves, without the aid of a neutral wedge, to give the correct light flux for 4 in. (10·16 cm) T2, 2 in. (5·08 cm) T1 or 8 in. (20·32 cm) T4 lenses. The use of a neutral-density wedge enables the light flux to be continuously varied so that, for example, the 4 in. (10·16 cm) T2

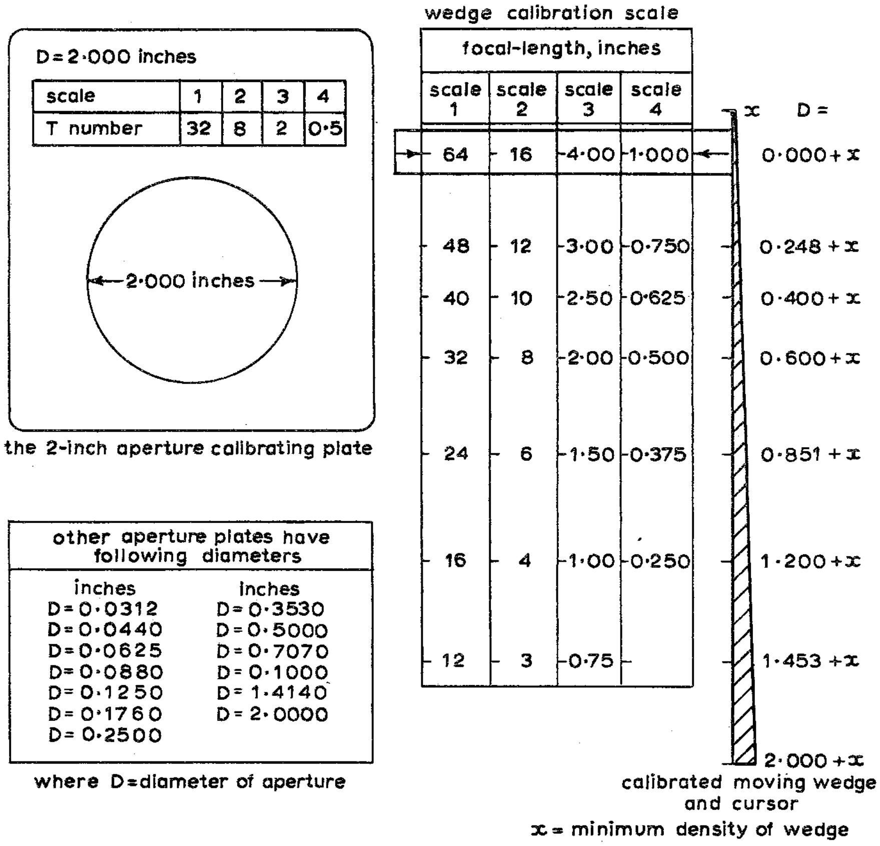

Fig. 3 - Standard aperture plate and neutral density wedge calibration

scale (scale 3 in Fig. 3) can be used for T2 lenses having focal lengths ranging from 4 in. (10·16 cm) to 0·75 in. (1·905 cm). The scale is graduated as follows:

Focal length (in.)	4·0	3·0	2·5	2·0	1·5	1·0	0·75
(cm)	10·16	7·62	6·35	5·08	3·81	2·54	1·905
Density of wedge	0	0·248	0·400	0·600	0·851	1·20	1·453

For this example

$$\text{focal length} = 4 \left\{ \text{antilog} \left(\frac{-D}{2} \right) \right\}$$

$$\text{or more generally } f = f_o \text{ antilog} \left(\frac{-D}{2} \right)$$

Where f_o = greatest focal length covered by the above scale.

D = required density of the wedge (more strictly, the required change in density from a low, but not zero, value at the commencement of the scale).

3.3. Calibration of Comparison Beams

Two sets of standard aperture plates having been made it is a simple matter to insert one of two identical plates in the comparison beam and the other in place of the lens under test. If the neutral wedge W_2, (Fig. 1), is set in its minimum density position, the flux through the two paths should be equal and a balance should be obtained on the oscilloscope display. If, for any reason such as dust on an optical element, the balance is offset, it may be restored by adjusting the small neutral wedge W_1 (Fig. 1) in the comparison beam. Duplicate pairs of plates of large and small aperture may be used to check whether any non-uniformity exists in the beam A as compared with the beam B (Fig. 1).

4. MEASUREMENTS

The description of wedge calibration has already illustrated how a lens can be calibrated in T numbers. There remain, however, the problems of checking lenses already calibrated in terms of T-number and the calibration and checking of lenses in terms of f-number.

Throughout the following measurement procedures it is assumed that the focal length of the lens is accurately known.

4.1. The Determination of T Factor

With the lens iris adjusted to the required f-number and using the standard aperture plate corresponding to the equivalent T-number, the wedge is adjusted for balance, as indicated on the oscilloscope.

Then the T factor $= \frac{F_1}{F_2}$

F_1 = the true focal length of the lens

F_2 = the setting of the wedge (calibrated in terms of focal length) for balance

4.2. To Check Lenses Already Calibrated in T-number

With the standard aperture plate in position and the lens iris set to the corresponding T-number, a balance is obtained by adjusting the wedge. The true T-number is then given by:

$$\text{T-number} = \frac{T_L \times F_1}{F_2}$$

T_L = the T-number indicated on lens

F_1 = the true focal length of lens

F_2 = the setting of the wedge for balance

Alternatively the iris of the lens can be adjusted until balance is obtained and the error on iris scale noted.

4.3. To Calibrate a Lens in Terms of f-number

If the transmission (τ) of the lens is known, the focal length F_1 of the lens may be multiplied by $\sqrt{\tau}$ giving F_2, to which the wedge should be set. This may be expressed as:

$$F_2 = F_1 \sqrt{\tau}$$

The standard aperture plates may thus be used as standards of f-number.

5. TOLERANCES (Quoted from ASA 6.2.1.)[3]

Each full stop interval for a lens calibrated in accordance with the T system shall be marked within an accuracy of 1/6 of a stop or 10% in illuminance or 5% in diameter. This assumes that the diaphragm is always closed down to the desired aperture (not opened up from a smaller aperture) to eliminate backlash effects.

6. CONCLUSION

With the increasing use of zoom lenses in addition to fixed-focus camera lenses, it is essential that a true indication of photometric aperture be indicated on the lenses. The use of T numbers provides such indication, and the method described provides a simple means of checking and calibrating the lenses.

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8. APPENDIX: DEFINITION OF TERMS

The following definitions are extracted from the proposed American Standard[3] for aperture calibration of motion-picture lenses.

8.1. f-number

The f-number of a lens represents a true geometrical measure of the relative aperture.

For a lens having a circular aperture, which is perfectly corrected for spherical aberration and satisfies the sine condition, and which is also assumed to form an image in air of a very distant object, the f-number of the lens is defined by the equation:

$$\text{f-number} = \frac{f}{D} = \frac{1}{2 \sin \theta} \qquad (1)$$

where f is the focal length, θ is the semi-angle of the cone subtended by the circular exit pupil of the lens at the point where the lens axis intersects the plane of the image of the assumed distant object, and the entrance pupil has a diameter, D.

If the entrance pupil is not circular, this relation becomes:

$$\text{f-number} = \frac{f}{D'} = \frac{f}{2}\sqrt{\frac{\pi}{A}} \qquad (2)$$

where f is the focal length, D' is the effective diameter of a non-circular entrance pupil, and A is the area of the entrance pupil aperture.

If the aperture is circular, but the lens does not satisfy the sine condition then f/D will not be equal to $1/(2 \sin \theta)$. In such a case, the f-number of the lens is to be defined by $1/(2 \sin \theta)$ rather than by the ratio f/D. This value is chosen because both the image illuminance* and the depth of field of the lens depend directly on $\sin \theta$. In such a lens then, the marked f-number will not be equal to the simple ratio of the focal length to the diameter of the entrance pupil.

In terms of f-number, the basic equation for image illuminance becomes:

$$E = \frac{\tau B}{4\ (\text{f-number})^2} \qquad (3)$$

where B is the luminance of the object and τ is the lens transmittance.**

8.2. Effective and Equivalent f-number of a Lens used at Finite Magnification

The effective f-number of a lens is that value which may be inserted into equation (3) to determine the image illuminance under the specific conditions in which the lens is used to form an image. It is defined as:

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* Image illuminance = image illumination.

** 'Transmission Factor' is the corresponding English term.

$$\text{Effective f-number} = \frac{1}{2 \sin \theta_m}$$

where θ_m is the semi-angle of the cone subtended by the circular exit pupil of the lens. θ_m changes as the magnification, m, increases.

By magnification is meant the ratio of the transverse dimension of the image to that of the object.

For an infinitely thin lens, or for a thick lens in which the entrance and exit pupil coincide with the first and second principal planes, respectively, and in which the light beam is limited only by the iris diaphragm, the effective f-number will be related to the f-number by:

$$(\text{Effective f-number for magnification m}) = (\text{f-number})\ (1 + m) \tag{4}$$

The equivalent f-number is a quantity defined for those lenses that cannot be regarded as being 'thin'; in such cases, the effective f-number at a finite magnification will not be equal to the infinity f-number multiplied by (1 + m). Inasmuch as it has become routine to multiply the marked f-number of a lens by (1 + m) in order to determine the effective f-number at a finite magnification, m, it is suggested that if a lens is designed to work at or near some particular finite magnification, m, the aperture marking should be engraved with the 'equivalent' f-number defined by:

$$\text{Equivalent f-number} = \frac{\text{Effective f-number at magnification m}}{(1 + m)} \tag{5}$$

8.3. T-number

The T-number is a photometrically determined measure of the relative aperture of a lens adjusted to take proper account of the lens transmittance, so that the illuminance in the centre of the lens field will be the same for all lenses at the same T stop setting. This assumes that the object is an extended, uniform, completely diffusing (Lambertian) surface.

For a lens used with a distant object the T-number is defined as the f-number of an ideal lens having 100% transmittance and a circular aperture, which would give the same central-image illuminance as the actual lens at the specified stop opening. Hence, for a lens with circular aperture:

$$\text{T-number} = \frac{\text{f-number}}{\sqrt{\tau}} \tag{6}$$

and for a lens with an entrance pupil of any shape and area A, the corresponding formula is:

$$\text{T-number} = \frac{f}{2} \sqrt{\frac{\pi}{\tau A}} \tag{7}$$

In practice, however, it is expected that the normal procedure will be to re-engrave the diaphragm ring on the lens at a series of definite T numbers, rather than to measure the T numbers corresponding to each of the existing marked f numbers.

Since the T numbers are determined photometrically they automatically take account of the size and shape of the aperture, the actual focal length of the lens, the lens transmittance, and any internally reflected stray light which may happen to strike the film at the centre of the field (such as in flare spot). It is implicit in the T-number system of aperture marking that the precision of the lens calibration shall be high.

For a lens designed to be used at finite magnification, the equivalent T-number will correspond to the equivalent f-number, defined by equation (6).

From the above proposed American Specification the definition of T factor can be stated as follows:

The T factor is the factor by which the f-number must be multiplied to produce the T-number.

As per definition $T = \frac{f}{\sqrt{\tau}}$

the T factor is equal to $\sqrt{\frac{1}{\tau}}$ (8)

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